A Highly-Stable 36 GHz GaAs FET DRO with Phase-Lock Capability

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Introduction

DROs are well suited for providing stable microwave and mm-wave signal sources in applications such as fixed frequency local oscillators.[1,2,3] In addition to their good frequency stability, their simplicity and relatively high efficiency, transistor DROs are easily adaptable to MMIC technology, which offers the potential for low cost, high volume production.

We describe the design of a dielectric resonator-stabilized oscillator operating at a frequency of 36 GHz with a frequency stability of 1 ppm/°C over the –55° to +85°C military temperature range and phase noise of –104 dBc at 100 kHz from the carrier frequency.

In addition, the circuit is capable of being electronically tuned over a frequency range of more than 400 ppm (15 MHz at 36 GHz). This capability is useful in several categories of applications. For example, 400 ppm of frequency tuning is sufficient to compensate for all predicted frequency drift and frequency shift due to component aging if the DRO is phase locked to a harmonic frequency signal of a stable HF reference oscillator.

Transistor and Resonator Criteria

A millimeter wave frequencies, a transistor suitable for use in an oscillator should have an F_{max} at least twice the required oscillation frequency and a MAG of 6 dB or greater at the operating frequency for reasonable power output. For a 36 GHz oscillator, the active device was an Avantek 0.25 μm gate-length, 75 μm gate-width GaAs FET, fabricated on vapor phase epitaxial material using the hydride process.[4] The measured gain of the transistor was 9.5 dB at a frequency of 45 GHz, and its measured F_T was 60 GHz.

An equivalent circuit model of the device was developed based on S-parameters measured at frequencies through 26.5 GHz. The model was then used to calculate S-parameters at the frequencies of interest.

The dielectric resonator was a cylindrical disk with dimensions of 0.063″ diameter by 0.025″ thickness made of Zr-Sn TiO_2 with a dielectric constant of 37.

By varying the composition of the dielectric material, suppliers of dielectric resonators offer a choice of temperature coefficients. Temperature-related variations in device and circuit parameters, as well as the degree of coupling to the dielectric resonator, affect the frequency vs temperature characteristics of the oscillator. This means that the required temperature coefficient of the dielectric resonator must be determined experimentally after a prototype oscillator is tested over temperature. For this design, a resonator with a temperature coefficient of +3 ppm/°C was selected. Using a Ka-band scalar analyzer, the unloaded Q of the resonator placed in an MIC circuit measures 720 at 36 GHz.[5]

Oscillator Design and Construction

There are two basic ways in which a dielectric resonator may be used to control the frequency of an oscillator: as a frequency "stabilized" DRO or as a frequency "stable" DRO.

In a frequency-stabilized DRO, the resonator is placed in the output plane of an otherwise free-running oscillator. This approach has the disadvantage of a tendency to frequency jumping, frequency hysteresis problems, higher insertion loss due to the resonator being coupled to the output circuit of the oscillator,

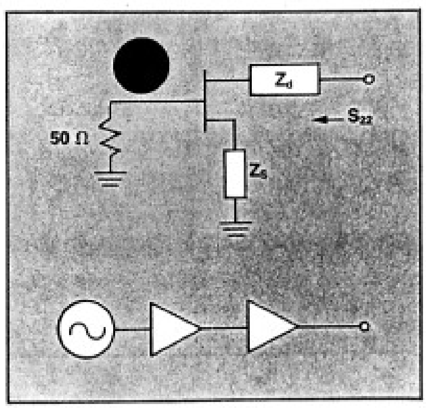

Fig. 1 Series feedback dielectric resonator oscillator circuit with the dielectric resonator on the gate side of the transistor.

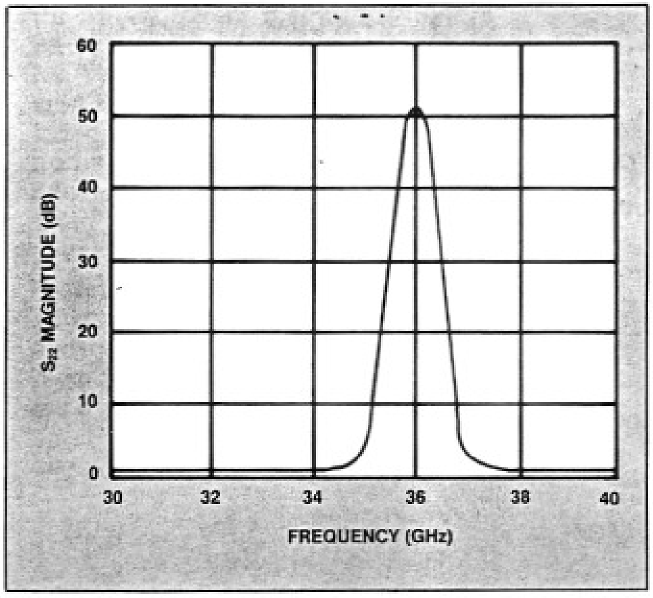

Fig. 2 Magnitude and phase of the reflection coefficient S'_{22} looking into the device drain.

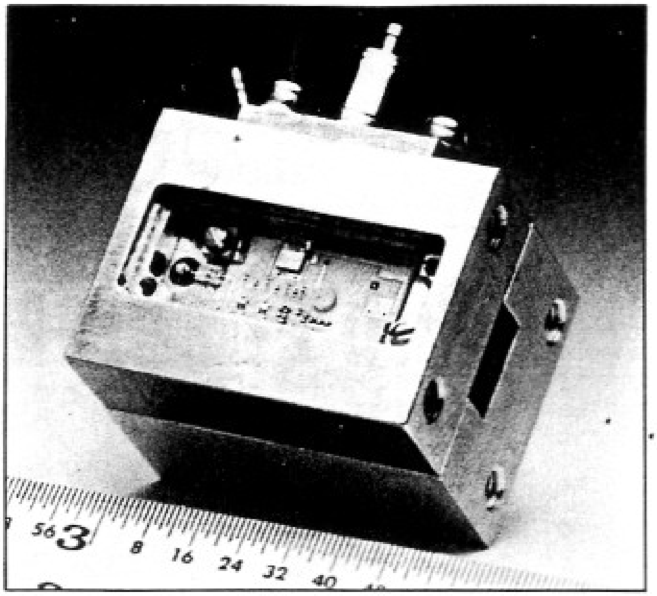

Fig. 3 The complete oscillator/amplifier assembly housed in a hermetically sealed package.

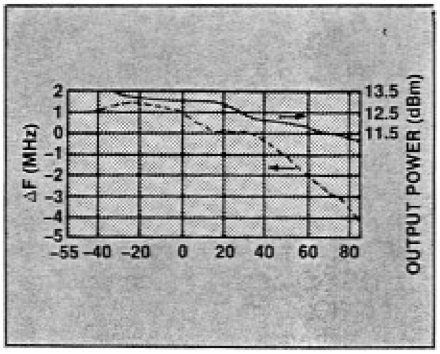

Fig. 4 Variation of DSO RF frequency and output power with temperature.

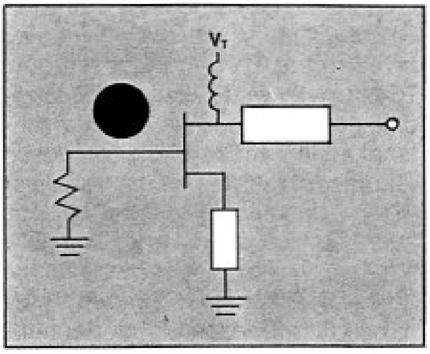

Fig. 6 Varying the FET bias provides a typical tuning range of 0.1 percent of the center frequency at mm-wave frequencies.

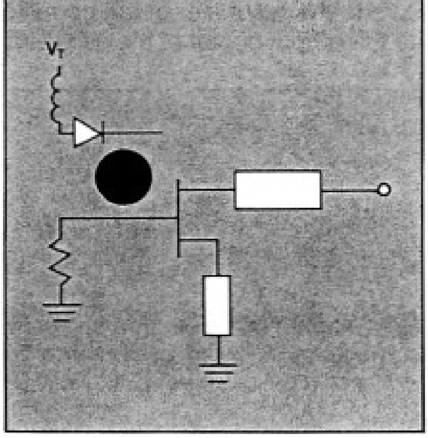

Fig. 5 The frequency of a DRO can be electronically varied by coupling to a line segment containing a varactor diode.

and a relatively high output power variation over frequency.

In a frequency-stable DRO circuit, the dielectric resonator is used as either a series or parallel feedback element and as the frequency-determining element in an oscillator. This design, used for the oscillator discussed here, offers greater DC-to-RF efficiency and greater resistance to mode jumping and hysteresis effects. It also is generally simpler to build and adjust than a frequency-stabilized circuit.

The oscillator circuit shown in Figure 1 is the commonly used drain-output, series feedback configuration, with the dielectric resonator on the gate side of the transistor.

By using the calculated three-port S-parameters, the source impedance, Z_s, was mapped into the S'_{11} plane of the device.[6] An inductance of 1.5 nH was used as the source impedance to generate the necessary instability in the device at around 36 GHz. Using a commercial CAD program, the position of the resonator and the drain impedance were optimized to satisfy the oscillation conditions at 36 GHz. The magnitude and phase of the reflection coefficient S'_{22} looking into the drain are shown in Figure 2, which indicates the oscillations at a frequency of 36 GHz.

Two narrowband amplifier stages using the same device as the oscillator were added to boost the output power and to limit frequency pulling with variations in load. The oscillators and amplifiers are constructed on a 10-mil alumina substrate using thin-film hybrid construction.

The GaAs FETs are typically biased at V_{DS} = 4 V, I_{DS} = 15 mA. In this design, an 8 V IC regulator supplies the DC bias power for biasing the amplifier stages, while the oscillator bias voltage is variable from 6 to 9 V. The complete oscillator/amplifier assembly is housed in a hermetically sealed package (Figure 3).

Performance as a Fixed-Frequency Oscillator

The oscillator/amplifier assembly produces an RF power output of +12

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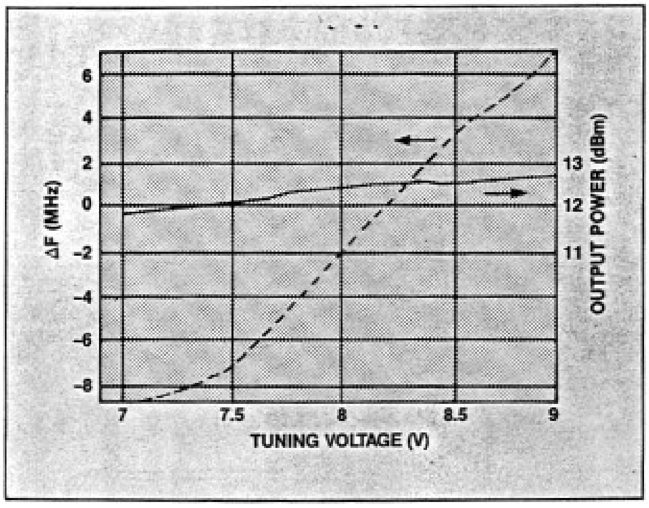

Fig. 7 Frequency and power variation of the bias-tuned DRO assembly with the oscillator bias voltage varied.

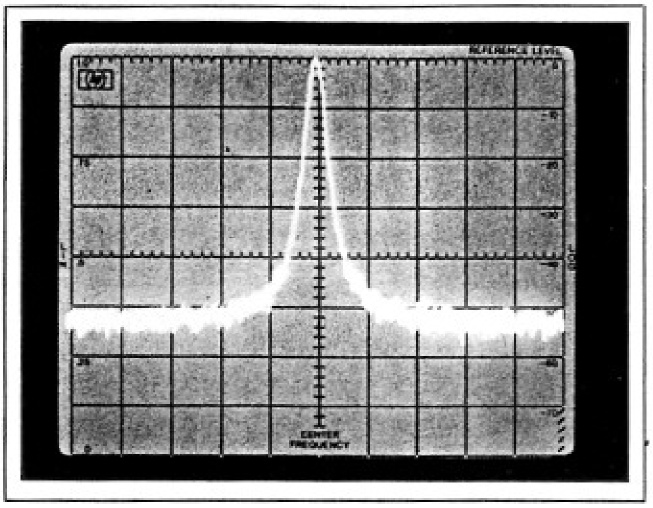

Fig. 8 Spectral purity of the 36 GHz DRO assembly.

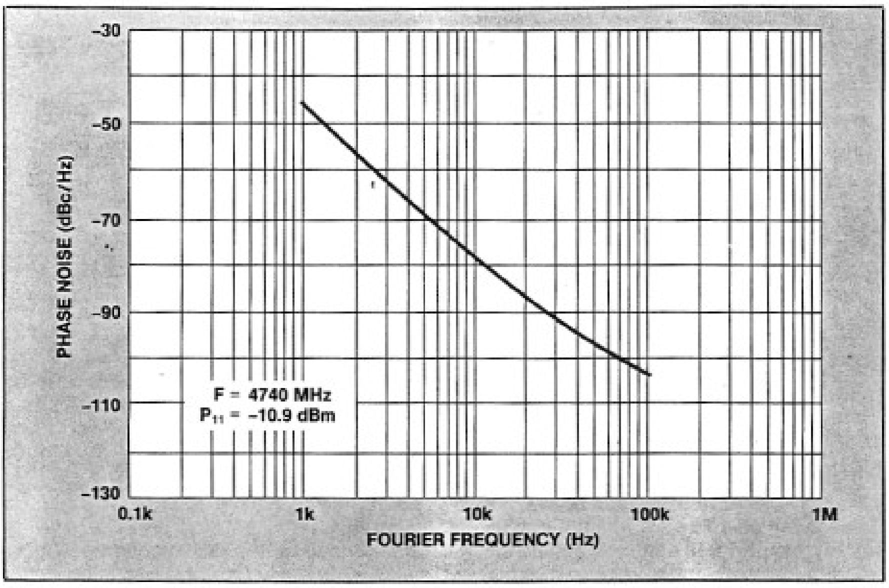

Fig. 9 Phase noise of the 36 GHz DRO assembly.

dBm at a frequency of 36 GHz and at a temperature of +25°C; minimum output power is +10 dBm over the −55° to +85°C military temperature range. Figure 4 shows the variation of RF frequency and power output with temperature. The pulling figure with the buffer amplifier was measured as 2 MHz with an SWR of 1.67.

Frequency Pushing is Preferable to Varactor Tuning

The frequency of a DRO can be electronically varied over a limited range by using several circuit techniques.[6] For example, the dielectric resonator can be coupled to a microstrip line segment containing a varactor diode (Figure 5). The mutually coupled resonant circuits permit one to tune the frequency of the DRO by 50 to 100 MHz at mm-wave frequencies.

The disadvantage of using varactors is that the parasitic capacitance of most available varactor diode chips is too high for effective use at mm-wave frequencies. Only a fraction of a pF of tuning capacitance is required at 36 GHz, and this is masked to a large extent by the parasitic capacitance of the diode chip.

Also, coupling a varactor into the resonant circuit substantially degrades the phase noise of the oscillator (by as much as 6 to 10 dB compared to the bias tuning technique described below). This is due to the decrease in loaded Q of the dielectric resonator when coupled simultaneously to two microstrip lines rather than one (Figure 5). Alignment of varactor-tuned DROs at the mm-wave frequencies is also difficult compared to alignment of a free-running or bias-tuned DRO.

Bias Variation Provides Sufficient Tuning for Phase Locking

The sensitivity of the transistor to changes in the bias voltage also may be used to provide a tuning range of typically 0.1 percent of the center frequency. This technique was used to provide a moderate tuning range for the DRO shown in Figure 6. Figure 7 shows the tuning range of 15 MHz; power variation of the assembly with the oscillator bias voltage ranges from 6 to 9 V. This is sufficient frequency variation to compensate for the frequency drift of the oscillator over temperature, load and power supply variations; this frequency variation simultaneously cancels predicted frequency changes due to component aging. Thus it is possible, for example, to phase lock the DRO to a crystal reference oscillator operating at VHF.

Low Phase Noise Design

Optimization of phase noise performance calls for several design considerations, as well as the use of a high Q dielectric resonator and a low noise active device.

Phase noise in a DRO depends primarily on the following factors:

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- Low-frequency noise inherent in the active device
- Device upconversion factor
- Loaded Q of the resonator.

The device upconversion factor is a measure of the efficiency of the device in converting low frequency noise into phase noise at the oscillator output frequency.

Designing a tunable DRO for low phase noise calls for optimization of the resonator coupling and optimization of the transistor bias voltage. Wider pushing bandwidth is generally an indicator of lower oscillator Q and the resulting higher phase noise. Thus, the pushing bandwidth must be just wide enough to provide the amount of frequency tuning necessary for the given application.

The spectral purity of the oscillator is shown in Figure 8. The phase noise was measured by downconverting the DRO frequency to Ku band using a very low noise dielectric resonator oscillator and a low phase noise double-balanced mixer. The downconverted signal then was measured using a spectrum analyzer and delay line discriminator setup. The measured results appear in Figure 9, which shows a phase noise of −104 dBc at 100 kHz offset from the carrier.

Frequency variation due to changes in load impedance or phase is minimized by using a high loaded Q resonator and by incorporating buffer amplifiers between the oscillator and external circuitry.

Frequency drift over temperature is minimized by selecting the temperature coefficient of the dielectric material, as well as adjustment of the coupling between the resonator and the microstrip line. For a given Q and coupling coefficient, the required temperature coefficient of the dielectric resonator material can be calculated.[7] Other factors that affect temperature-related frequency drift are shielding, package design and characteristics of the adhesive used to attach the resonator to the substrate.

Acknowledgments

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